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Landscape complexity and soil moisture variation in south Georgia, USA, for remote sensing applications

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Summary This research addressed the temporal and spatial variation of soil moisture (SM) in a heterogeneous landscape. The research objective was to investigate soil moisture variation in eight homogeneous 30 by 30 m plots, similar to the pixel size of a Landsat Thematic Mapper (TM) or Enhanced Thematic Mapper plus (ETM+) image. The plots were adjacent to eight stations of an in situ soil moisture network operated by the United States Department of Agriculture-Agriculture Research Service USDA-ARS in Tifton, GA. We also studied five adjacent agricultural fields to examine the effect of different landuses/land covers (LULC) (grass, orchard, peanuts, cotton and bare soil) on the temporal and spatial variation of soil moisture. Soil moisture field data were collected on eight occasions throughout 2005 and January 2006 to establish comparisons within and among eight homogeneous plots. Consistently throughout time, analysis of variance (ANOVA) showed high variation in the soil moisture behavior among the plots and high homogeneity in the soil moisture behavior within them. A precipitation analysis for the eight sampling dates

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throughout the year 2005 showed similar rainfall conditions for the eight study plots. Therefore, soil moisture variation among locations was explained by in situ local conditions. Temporal stability geostatistical analysis showed that soil moisture has high temporal stability within the small plots and that a single point reading can be used to monitor soil moisture status for the plot within a maximum 3% volume/volume (v/v) soil moisture variation. Similarly, *t*-statistic analysis showed that soil moisture status in the upper soil layer changes within 24 h. We found statistical differences in the soil moisture between the different LULC in the agricultural fields as well as statistical differences between these fields and the adjacent 30 by 30 m plots. From this analysis, it was demonstrated that spatial proximity is not enough to produce similar soil moisture, since *t*-test's among adjacent plots with different LULCs showed significant differences. These results confirm that a remote sensing approach that considers homogeneous LULC landscape fragments can be used to identify landscape units of similar soil moisture behavior under heterogeneous landscapes. In addition, the in situ USDA-ARS network will serve better in remote sensing studies in which sensors with fine spatial resolution are evaluated. This study is a first step towards identifying landscape units that can be monitored using the single point reading of the USDA-ARS stations network.

Introduction

In the heterogeneous agricultural landscape within the Little River Watershed (LRW) in south Georgia, an in situ network of 27 ground stations was established in 2002 and 2003 as a source of ground-based point data to validate remote sensing analyses of soil moisture, soil temperature and climate and for long term hydrological studies in the southeastern United States (Bosch et al., 2006). During an intense field campaign in the Summer of 2003, field soil moisture and meteorological data were collected in the context of the USDA-NASA Soil Moisture Experiment 2003 (SMEX03) with the purpose of validating satellite remote sensing data from sensors such as the Advanced Very High Resolution Radiometer (AVHRR), Advanced Microwave Scanner Radiometer (AMSR) and the Advanced Synthetic Aperture Radar (ASAR), among others (Bindlish et al., 2003; Bosch et al., 2006; Cashion et al., 2005).

In highly fragmented and diverse landscapes, the uncertainty of the soil moisture estimates from remote sensors is likely to increase by using sensors with coarse spatial resolution. Under coarse spatial resolution, the ground area of the pixel value is larger than the landscape fragment sizes for soil, landuses/land cover (LULC) and topography. Thus, the pixel reflectance value in the image will comprise a mix of different soil moisture behaviors (Moran et al., 2004). During SMEX03, temporal stability geostatistical analysis demonstrated that each one of the in situ devices at the LRW produces reliable information of the soil moisture conditions and that data collected at each location is also stable throughout time (Bosch et al., 2006). However, when using satellite remote sensing data from the Tropical Rainfall Measurement Mission Microwave Imager (TRIMM) and the Moderate Resolution Image Spectro Radiometer (MODIS), the works of Cashion et al. (2005) showed that under a complex landscape such the LRW, remote sensors with coarse spatial resolution in the magnitude of several square kilometers produce inaccurate estimates of the soil moisture conditions. They suggested that satellite remote sensing data with an effective field of view (EFOV) less than a square km could better capture the spatial heterogeneity of the landscape at the LRW and, therefore, improve estimations of the soil moisture behavior.

Our objective was to investigate the spatial variation of ground-based soil moisture point data collected from small plots (30 by 30 m) matching in area the ground resolution of small EFOV remote sensors within the heterogeneous LRW landscape. Our goal is to assess the suitability of using small plots for field validation of satellite remote sensor instruments with small EFOV (<30 m) such as the multispectral scanners of the Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), radar sensors on RADARSAT and the thermal infrared sensors in Advanced Spectral Thermal Emissions Radiometer (ASTER) and Advanced Land Imager (ALI), all are expected to better capture local field conditions under landscape environmental complexity.

We hypothesize that despite the heterogeneity of the LRW at the landscape scale, it is possible to find temporally and spatially homogeneous soil moisture behaviors within small areas (30×30 m) and at different landscape locations. Therefore, within those plots and, as a consequence of homogeneous soil moisture conditions, a single point measurement can be used to represent soil moisture behavior of the 30 by 30 m area. We also evaluate if homogeneous soil moisture conditions can be identified within the areas regardless of their LULC and if each LULC exhibits a unique soil moisture behavior that is different from the others. In this case, the objective is to study the soil moisture variation within five dominant LULCs in the LRW landscape.

As a contribution to the continually advancing field of remote sensing of soil moisture, our results increase field knowledge and will lead to a better interpretation of the satellite estimates. This research also offers an opportunity to increase field knowledge of soil moisture behavior in heterogeneous landscapes towards linking fine spatial resolution data with ground measurements for broad scale estimations of soil moisture.

Methodology

Study area

The plots evaluated in this study are located at the north-eastern portion of the 334 km^2 Little River experimental watershed in the South Atlantic coastal plain of the United States, near Tifton, Georgia (Fig. 1). The watershed has relatively flat topography characterized by broad floodplains with poorly defined stream channels and gently sloping uplands varying from 1% to 5% (Bosch et al., 2007a). The typical soil for the area is a sandy loam with a sandy surface horizon and a heavier textured subsoil. This type of soil presents low water holding capacities, with a fast surface drainage. The annual average precipitation is approximately 1200 mm (Bosch et al., 2007b). Rainfall is unevenly distributed throughout the year with short-duration rains during the winter and high-intensity thunderstorms during the summer. While summers are long, hot and humid, winters are short and mild. The landscape is composed of a diversity of LULC including forest, cropland, pasture, residential areas and wetlands. Animal production is combined with agricultural activities yielding year-round production of vegetables and row crops (Bosch et al., 2004; Cashion et al., 2005).

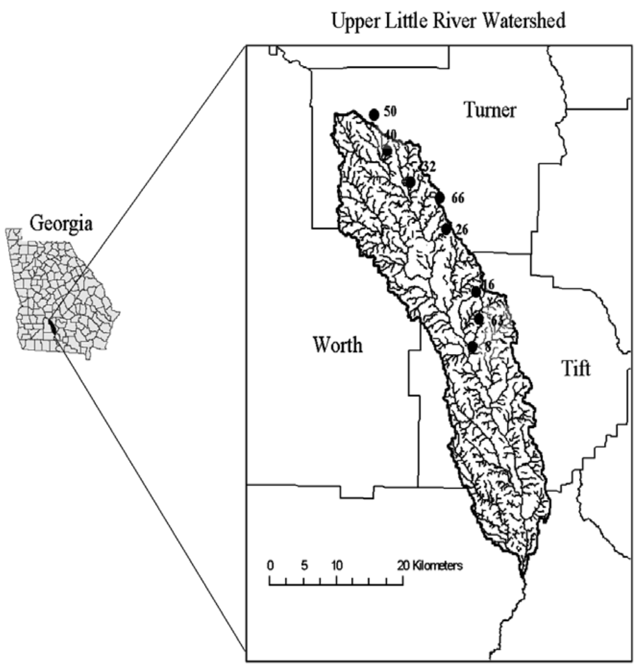

Figure 1 Location of the Little River Watershed in southeastern Georgia US and the sampling locations. The location of the sites is approximate to their true geographic location.

The in situ network operated by the USDA-ARS-SEWRL at the LRW is composed of 27 stations equipped with Stevens-Vitel Hydra-probes (Stevens Water Monitoring Systems Inc.) recording soil moisture information and ground temperature at three soil depths (5, 20 and 30 cm) every 30 min. Hydra-probes measure a dielectric constant for the soil and convert it to volumetric soil moisture based upon a factory provided calibration equation (Campbell, 1990; Gaskin and Miller, 1996). The Hydra-probe stations are typically installed along agriculture field boundaries, fence rows, and in some cases pasture areas and are typically surrounded by native grass vegetation. The network was established in 2002 as one of the sites for the SMEX03 study (http://hydrolab.arsusda.gov/smex03/SMEX03v5.pdf). Since 2002 continuous records have been used in hydrological studies (Bosch et al., 2004) and in remote sensing analysis (Cashion et al., 2005).

Plot data collection

A sub-set of eight of the 27 sites was selected for detailed analysis of spatial and temporal variability of soil moisture in the general area surrounding the Hydra-probes. Eight plots associated with the in situ soil moisture monitoring stations were selected for this research considering the logistical and practical constraints of access and completing field measurements within the same day (Table 1). A 30 by 30 m area surrounding the Hydra-probe was defined and subsequently sampled for soil moisture. Soil moisture was measured using a portable Theta capacitance probe (Dynamax Inc., ML2X Theta probe) that measures dielectric conductivity similar to the Hydra-probe explained above. The accuracy and reliability of this equipment in obtaining soil moisture point data were demonstrated by Jacobs et al. (2004) and Bosch et al. (2006), among others. In the same study area of our research the work of Bosch et al. (2006) showed that Theta probe readings present a relatively good agreement with gravimetric analysis of soil moisture, but that micro topography and the variation within small sam-

Table 1 Location, soil information and annual precipitation for the study sites

Site	*Y* coordinate	*X* coordinate	Elevation (m)	Land cover	Soil map units[a]	Total PPT 2005 (cm)
8	3,483,121.23	257,897.5	120	Grass	Ocilla	150.2
16	3,494,245.16	256,307.44	123	Grass	Tifton	150.2
26	3,502,328.72	252,215.12	115	Row crop	Alapaha	147.7
32	3,507,196.64	249,514.28	123	Grass	Tifton	140.5
40	3,511,504.48	246,611.08	134	Row crop	Tifton	141.0
50	3,516,116.84	244,911.43	113	Grass	Sunsweet	151.3
63	3,490,204.59	258,057.01	110	Grass	Fuquay	132.4
66	3,504,345.43	256,398.32	116	Bare soil	Tifton	138.0

http://www.soils.usda.gov/survey/geography/ssurgo/.
[a] A full description of the soil map units can be found at USDA-National Resource Conservation Service (USDA-NRCS) Soil Survey Geographic Database (SSURGO).

ples may increase errors within the gravimetric reading. In this case Theta probe readings averaged 6.6% lower than gravimetric readings. To minimize the effects of human errors and systematic errors in our research, soil moisture readings were collected with the same equipment on all dates and operated by the same personnel.

Three different soil moisture datasets were collected during eight campaigns throughout 2005 and January 2006. The first dataset consisted of data collected randomly within the eight 30 by 30 m plots. The purpose of the random sampling method was to characterize the overall spatial variability of soil moisture within the plot boundaries. The in situ Hydra-probe stations studied were: sites 8, 16, 26, 32, 40, 50, 63 and 66 (Fig. 1). For each plot, 10–20 readings were collected on four different dates: March 11, March 28, April 12 and May 24 of 2005.

The second dataset was collected with the purpose of testing temporal stability of the soil moisture readings over a fairly short time period (48 h). Two sets of soil moisture samples were obtained from the plot areas on two consecutive days, November 30 and December 1 of 2005, and January 13 and January 14 of 2006. A systematic sampling process in which the location of each reading was known and kept constant for each of four subsequent sampling dates was followed. Each reading was taken at 3 m intervals in four directions from the Hydra-probe station collecting a total of 20 samples per plot. An ideal configuration of the sampling procedure is presented in Fig. 2, with four perpendicular directions. However adjustments in the angles of the directions were made at some locations to avoid landscape variations and to preserve plot homogeneity. At some locations, fewer than four directions were evaluated due to the presence of obstacles such as roads or channels.

A third soil moisture dataset was collected from five fields adjacent to the plot areas under the LULC's grass, orchard, bare land and agriculture. The agriculture landuse was represented by two fields, one with peanuts and one with cotton. From each landuse, eight to ten soil moisture readings were collected with the theta probe at 3 m intervals along a 25–30 m transect. Each sampling location was recorded and revisited four different times in November–December 2005 and January 2006 coincident with the plot sampling. The grass, orchard, bare land and agriculture transects were associated by their close distance with the Hydra-probes sites: 50, 32, 66 and 40, respectively.

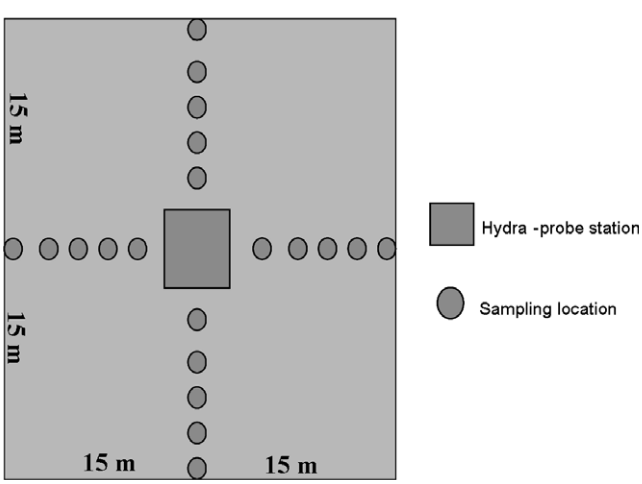

Figure 2 Ideal soil moisture field sampling at 3 m intervals within a 30×30 m area.

Precipitation records for each site were obtained from rain gages at the Hydra-probe stations, extracted for a 12-day period at intervals of 5 min and aggregated by day for each one of the sampling dates.

Statistical analysis

Time stability analysis, one way analysis of variance (ANOVA), Tukey and Tamhane post hoc analysis, Pearson's correlation coefficient, general linear model, and t-test were used to analyze the data. Time stability analysis requires calculating the mean of the volumetric soil moisture content at different points within the plot. This average value is defined as the field mean. Using the field mean, Vachaud et al. (1985) present the mean relative difference and the variance of the relative difference as the standard test for time-stable point assessments. Mean relative difference is an indicator of the bias of a sample from the mean. The variance is an indicator of the precision of that reading. As an overall estimation of the time stability of a site within a field, the RMSE of mean relative difference combines both metrics. Points exhibiting a low RMSE are the most time stable within the studied area (Jacobs et al., 2004). The advantages of these tests have been discussed in the works of Grayson and Western (1998) and Mohanty and Skaggs (2001).

The purpose of the mean relative difference is to measure, through time, how a particular site compares to the average of all the sites, indicating if the site is wetter or drier than the mean across the sites. If the mean relative difference for a site is close to zero, that particular point-site can accurately estimate the mean of the field. Grayson and Western (1998) and Cosh et al. (2004) formulated the mean relative difference as

$$\bar{\delta}_i = \frac{1}{n_t} \sum_{t=1}^{n_t} \frac{S_{i,j,t} - \bar{S}_{j,t}}{\bar{S}_{j,t}} \tag{1}$$

where n_t is the number of sample sites, S_{ijt} is the jth sample at the ith site at time t of n sites within the sample area, and $\bar{S}_{j,t}$, the sample area mean is the computed average among all sites for a given date and time j ($j = 1-t$).

The variance of the relative difference characterizes the precision of the point measurement. Jacobs et al. (2004) formulated the variance of mean relative difference as

$$\sigma(\delta)^2_{i,j} = \frac{1}{n_t - 1} \sum_{t=1}^{n_t} \left(\frac{S_{i,j,t} - \bar{S}_{j,t}}{\bar{S}_{j,t}} - \bar{\delta}_{i,j} \right)^2 \tag{2}$$

In addition to these tests, the Person's coefficient of correlation (Cosh et al., 2004) is presented as a complementary test to determine site time stability. The Pearson's correlation coefficient is defined by Cangelosi et al. (1976) as an abstract measure of the degree of relationship between two variables. This coefficient corresponds to the square root of the coefficient of determination that considers the proportion of variation in one population-variable that is explained by the variance of another population-variable. The Pearson's coefficient of correlation will compute the correlation of the soil moisture pattern between two days. Highly correlated patterns have values close to 1, uncorrelated patterns have values close to 0 and inversely correlated patterns have values close to −1.

ANOVA is a statistical test that compares variation within the individual samples of a group, as well as the variation between groups from a sampling process. In this analysis an F value is generated and a statistical significance for the difference between and within groups can be established at probability levels of 0.05, 0.01 or less. In this research, ANOVA analyses were performed to compare the soil moisture behavior among the eight plots and to find plots that are similar in soil moisture behavior. A general linear model with factor analysis is a modification of the ANOVA test that divides the sources of variation within the groups by associated factors. This analysis was used to find directional effects within the plots.

In all the instances where statistical significance was found, a post hoc test was performed to detect the groups for which the difference shows significance. The Levenne homogeneity test was performed to decide which post hoc analysis to choose. When homogeneous variance within the groups was detected, a Tukey test was applied and Tukey groups of similar behavior were formed. In the scenarios in which the variance was not homogeneous, the Tamhane post hoc test was used.

A general two-paired t-test was computed to establish the significance of the difference between the soil moisture patterns from two simultaneous dates. This test will be described in more detail within the results section below.

Results

Soil moisture variation between and within plots

Precipitation analysis

The number of rainfall events for the 12-day period previous to the sampling date ranged between 3 and 6. The minimum average precipitation across the sites in a rain event was less than 2.5 cm, observed in the twelve days prior to May 24. The maximum average was 10 cm, observed in the twelve days prior to March 28. Under these precipitation conditions, the field work included at least one dry condition on May 24, one wet condition on March 28 and two intermediate conditions on sampling days April 11 and March 11 (Table 2 and Fig. 3). In general, the four dates of systematic sampling (November—December 2005 and January 2006) were conducted under drier conditions than the random sampling in early 2005, excepting the May reading (the driest one).

The precipitation records for the 12-day period prior to field soil moisture data collection showed that during rainfall events all the sites received simultaneous precipitation with small variations among them. The ANOVA of the precipitation events supported this observation with no significant difference at 0.01 probability level among locations for any of the 12-day periods before field data collections. This indicates that the water supply was homogeneous for all the sites prior the field data collections and, therefore, the differences in moisture conditions on the ground can be considered as the result of intrinsic environmental conditions acting within the field and mostly independent of water supply.

Soil moisture descriptive statistics

The mean volumetric soil moisture and the infield variation recorded for eight locations at each of the eight field data collection dates are presented in Fig. 4. In general, the periods of maximum and minimum soil moisture values correspond to the periods of maximum and minimum cumulative precipitation. The driest and wettest conditions match the cumulative precipitation values observed during the 12-day period before the sampling. However, closer inspection of these data reveals site differences in soil moisture that are not explained by precipitation trends. The soil moisture records show site 8 with the highest values of volumetric soil moisture while site 40 has the lowest values of volumetric soil moisture for most of the sampling dates. When compared with the precipitation record, site 8 presented the greatest cumulative precipitation only for three of the sampling dates, while sites 63, 16 and 50 have the greatest precipitation inputs for the five others dates. The lowest soil moisture values were found at sites 32 and 40. The precipitation records shows site 32 with greater precipitation than the average and site 40 with rainfall above average for two sampling dates and less than 1.25 cm of rain below average for three of the sampling dates. These observations support the hypothesis that within the eight sampling plots, soil moisture has a site specific behavior caused by intrinsic environmental variables beyond precipitation acting at the local scale.

The descriptive statistics showed the standard deviation for the soil moisture in the range of 0.7% and 4.8% with an average of 2.8% when considering all the datasets together. The research of Anderson et al. (2004), found that high standard deviations were associated with soils approaching either the wet or the dry limits. In our results, there is

Table 2 Summary of 12 day precipitation records prior to field data collection

Sampling date	Average total PPT/site (cm)	Maximum total PPT/site (cm)	Minimum total PPT/site (cm)	No. rain events	Average No. of rain events
March 11, 2005	15.1	17.9	13.2	4	1.4
March 28, 2005	39.4	49.5	25.9	6	2.6
April 11, 2005	30.9	33.8	28.2	5	2.4
May 24, 2005	6.3	14.0	2.2	6	0.5
December 01, 2005	13.8	21.0	0.9	6	1.0
January 14, 2006	7.5	13.8	4.6	3	0.9

not a clear trend between soil moisture levels and standard deviation.

Analysis of variance (ANOVA) of soil moisture

The difference between soil moisture conditions across the eight plots for the different reading dates was explored using a one way ANOVA. This analysis uses two sets of variation to perform a comparison between the plots. The variation within groups accounts for the differences among all the sample points collected within a field on a given date. The variation among groups compares the overall variation among the plots for a given date. The statistical significance of the analysis is set at the probability level of 0.05 or 0.01.

The ANOVA for the eight plots showed high statistical differences in soil moisture for all the sampling dates with significance below the 0.01 probability level. A large range

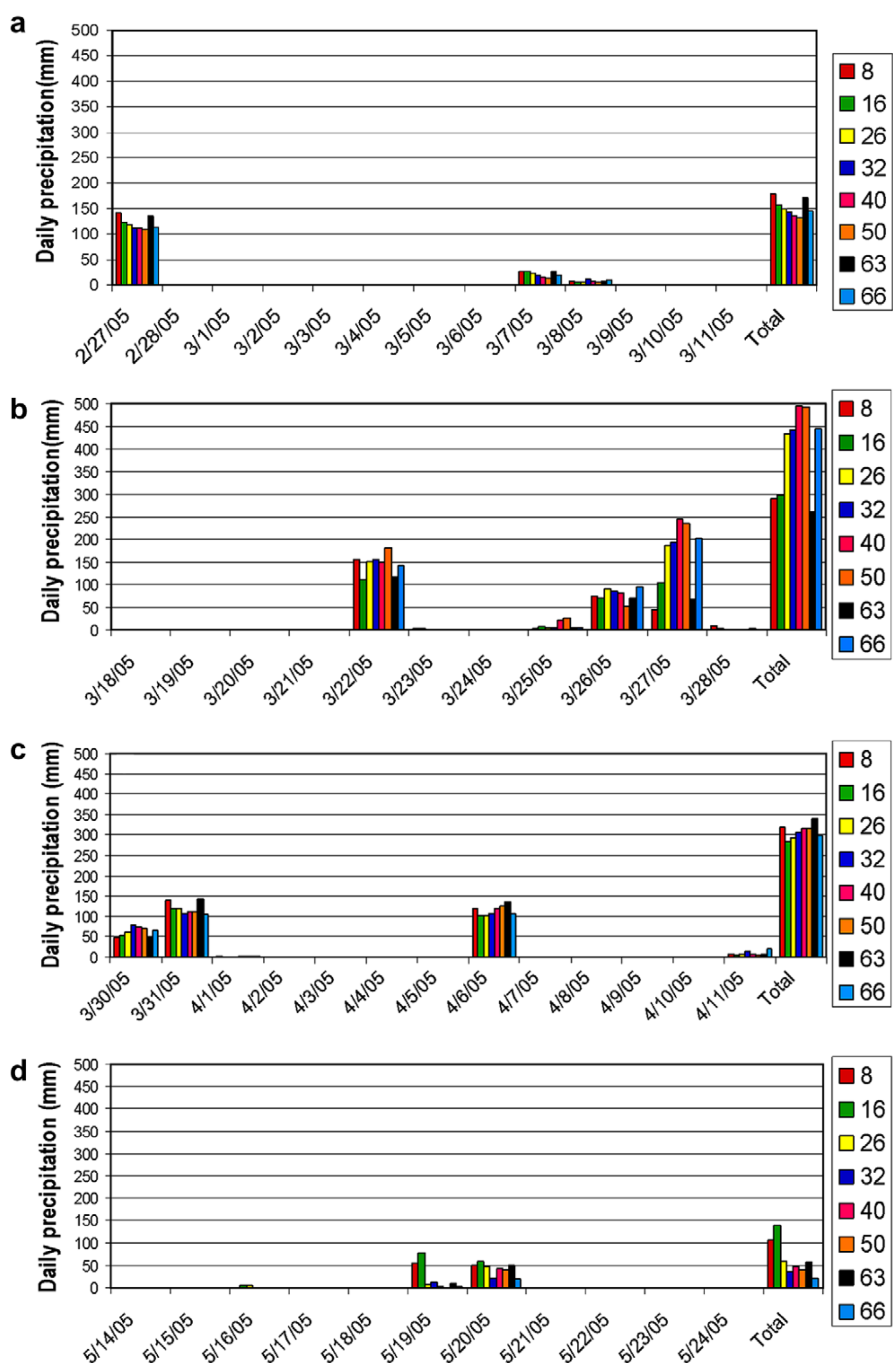

Figure 3 Actual precipitation at the sampling sites for the field data collections dates of March 11 (a), March 28 (b), April 12 (c), May 24 (d), and November—December (e) of 2005, and January of 2006 (f).

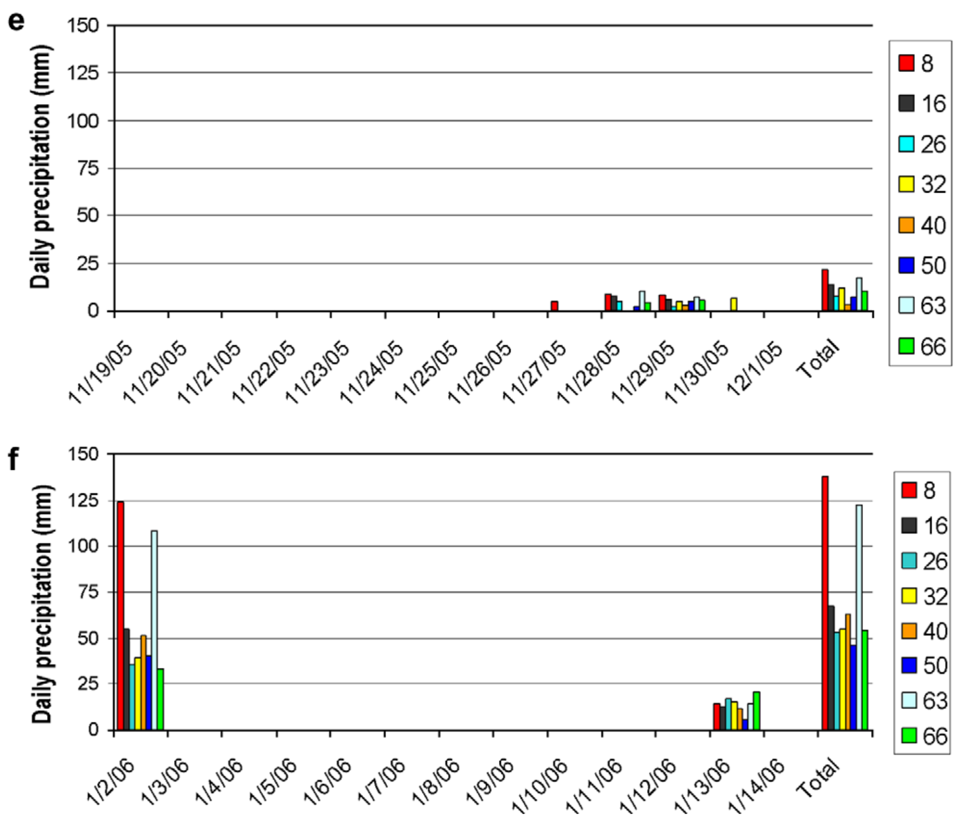

Figure 3 (*continued*)

(33.1 and 237.9) in the mean squares between groups, and within groups (*F* value) confirms the variation in soil moisture behavior among the plots already suggested by the descriptive statistics. The low values for the within groups mean square score showed by the ANOVA indicate low soil moisture variation within a given plot which suggest a homogeneous behavior of the soil moisture within the 30 by 30 m area.

The Tukey post hoc test was used to explore in more detail the variability among groups shown to be significant different by the ANOVA. The Tukey test conducts a multiple comparison among the plots, creating groups with similar responses for the studied variable significant at the probability level of 0.05. Table 3 summarizes the Tukey groups formed in one by one comparison between sites. The number of times a pair of plots is placed together indicates the strength of the similarity between plots. In this case the strongest relationships were found between pairs 26 and 32, 32 and 66 and 50 and 63 which were grouped together six times, while the weakest relationships were found between pairs 8 and 26, 8 and 40, 8 and 66 and 40 and 50. Site 8 was found with the most unique soil moisture behavior, while site 66 presented a high level of similarity with other sites.

The similarity between soil moisture conditions at sites 26 and 32 can be explained by the precipitation record and the soil type since both sites received similar amounts of rainfall with less than 2.5 cm of difference for all the sampling dates and both sites belong to the Tifton soil series thus sharing similar soil characteristics.

The vegetation cover in the 30 by 30 m plot surrounding site 32 is a short grass, while site 26 is located at the edge of an agriculture field in which hay is cut for cattle consumption. Similarities between sites 16 and 50 are not explained by the precipitation record since the difference in cumulative rain is more than 10 and even 18 cm of rain. These soils also differ in soil type since 16 is in the Tifton series while site 50 is in the Sunsweet series (Table 1). However, vegetation cover is similar since a homogeneous grass is present in both of them. These sites also are exposed to transit of agriculture equipment that may influence the soil physical characteristics.

As previously mentioned, the most dissimilar sites were the pairs 8—26, 8—40, 8—66, 40—50 and 50 and 32. To a lesser degree, low association was found between sites 16 and 32 in a total of six of the sampling dates. The pairs 8—26, 8—40, 8—66 present different combination of soil type and land use that can be responsible of variations in the water infiltration process and therefore in the soil moisture content. In the case of sites 40 and 50,the differences of cumulative rain were less than 2.5 cm in four occasions, and on three occasions for the differences between sites 50 and 32. For the pair 50 and 32, there were two occasions with high differences in cumulative rain and two occasions with very close total rain, indicating once again the secondary influence of precipitation in the variation between plots.

After the cropping season was over, the agriculture field adjacent to site 40 previously planted with peanuts remained bare and without vegetation cover. This condition is similar to site 66 in which an important number of point samples were taken from the bare-soil section of the field. This observation suggest that at the LRW, LULC is a greater factor affecting soil moisture conditions than cumulative

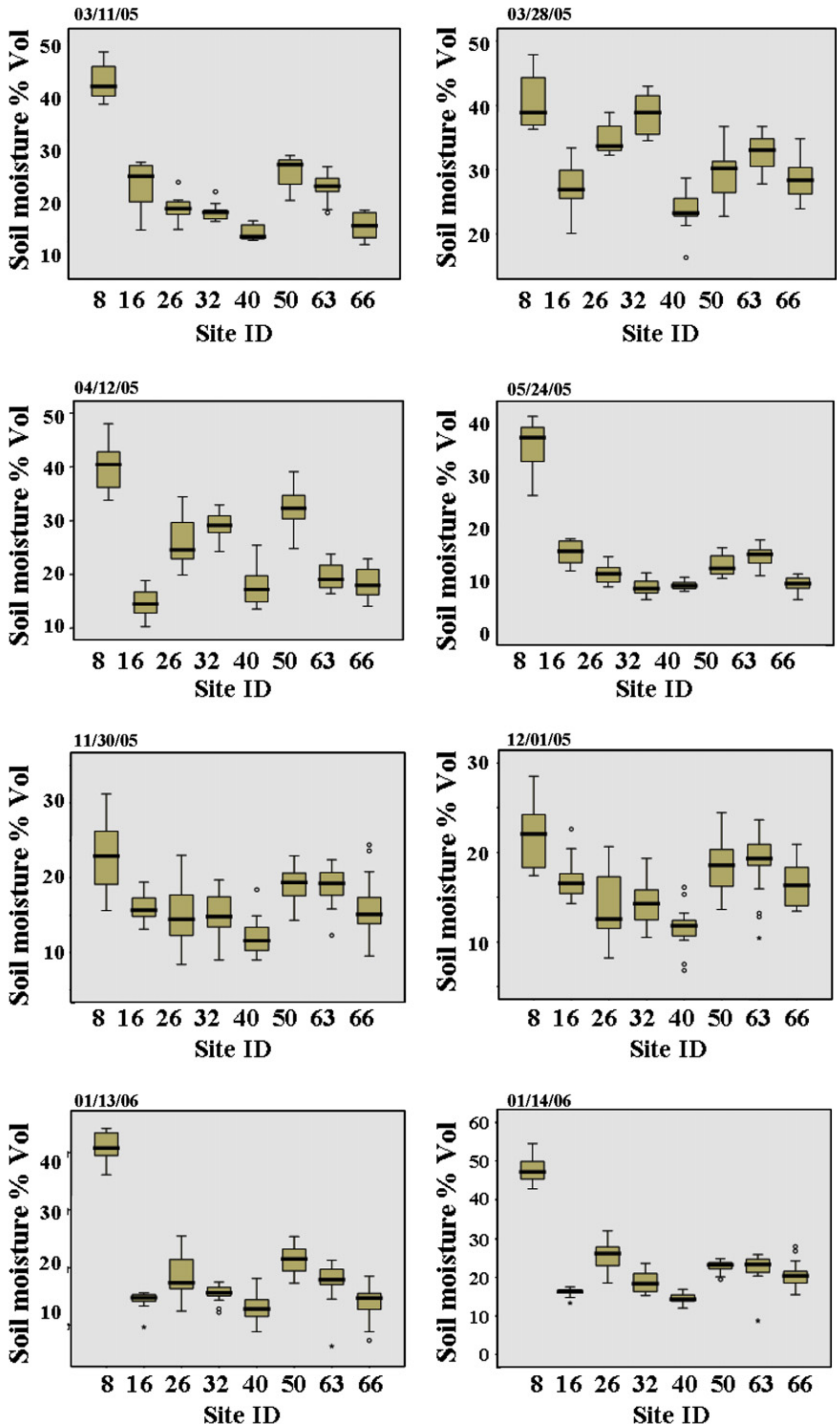

Figure 4 Soil moisture descriptive statistics for eight data collection locations. (Values in the (*y*) axis were automatically generated to fit the data.)

precipitation since there are differences of 2.5 and 5 cm of cumulative rain between site 40 and 66, while other sites with less than 2.5 cm of precipitation difference were not grouped with them.

The influence of LULC in soil moisture indicated by our results is particularly important under the LRW landscape considering the long tradition of row-crop agriculture and its different evapotranspiration and soil water usages when compared with other landuses. Under row-crop agriculture, vegetation cover follows the phenological stages of the crops evolving from bare land during the sowing season to partially or fully vegetation cover during growing stages presenting dynamic patterns of soil surface evaporation that are different from those present in fully vegetated LULC. From a remote sensing perspective, the temporal dynamic within agriculture fields suggest that soil moisture retrieving

Table 3 Tukey groups of similar soil moisture conditions

Sites	8	16	26	32	40	50	63	66	Total
8		1	0	1	0	2	2	0	6
16	1		2	2	4	5	4	5	23
26	0	2		6	3	3	4	4	22
32	1	2	6		5	1	2	6	23
40	0	4	3	5		0	1	4	17
50	2	5	3	1	0		6	3	20
63	2	4	4	2	1	6		5	24
66	0	5	4	6	4	3	5		27
Total	6	23	22	23	17	20	24	27	0

algorithms that account for the variation of vegetation cover such as those described by Carlson et al., 1995 and Merlin et al., 2006 are expected to disclose better soil moisture estimates.

However, the spatial resolution of the remote sensing sensor most appropriate to capture soil moisture conditions under this landscape will be defined by the landscape fragmentation, LULC composition and the sizes of the LULC fragments. Preliminary work in this regards suggest high levels of landscape fragmentation at the LRW with fragments of small sizes (Giraldo, 2007). Therefore, moderated to fine spatial resolution sensors ($\approx$30 m) are expected to better suit the continuous study of soil moisture at the LRW.

Soil moisture time stability

The purpose of the parameter mean relative difference was to measure how a particular sampling location compared to the average soil moisture of the 30 by 30 m plot, indicating if the sampling location was wetter or drier than the across plot mean. This analysis serves also as an indicator of the in-field variation of surface soil moisture. In this regard, the results for the November–December plot data collections showed plot 26 with the highest range on mean difference with values between −36% and 39%, while the sites 16 and 50 showed the lowest variation with ranges between −12% and 19% and −19% and 16%, respectively. For the January plot data collections, the mean relative difference in variation decreased for all the plots when compared with the November–December, although site 26 was still the highest one (−19% and 26%). Field 8 showed the lowest variation with a range between −4% and 4% of mean relative difference (Fig. 5d).

When analyzing the two samples together (November–December and January), the mean difference (Fig. 5c) showed a high level of homogeneity within each of the sampled plots. The highest average of mean relative difference was 2.6% in site 66, followed by sites 8, 16 and 26 with values of 2.1%, 1.2% and 1.0%, respectively. For all the other sites, the mean relative difference was 0.1% below the plot mean and even as low as <0.04% on sites 40 and 50, showing these two plots as the most homogeneous ones. Since the mean differences approached zero, these results indicate that the sampling points within the plots are very close to each plot mean and, therefore, can accurately estimate the surface soil moisture behavior of the entire 30 by 30 m plot.

Our results show a high level of infield homogeneity that contrast with the results of similar research performed in larger plots. For instance, the works of Bosch et al. (2006) in the Little River Watershed showed that at the landscape scale, measures made with a hand carried Theta probe can represent the field mean by only 3–12% of the mean relative difference. The highest range of readings that over and under estimating the plot mean were observed on site 66 (−26% and 30%) and site 16 (−30% and 29%) and the lowest ranges were observed in sites 40 and 50 (−11% and 13%).

The work of Jacobs et al. (2004) showed variability in the range of 4% and 24% of the mean relative difference in 800 m agriculture fields, explained as variations in the hill slope position, and by heavy textured soils conditions with high percentage of clay. In our research, by selecting small landscape fragments, the in-field heterogeneity caused by topographic differences was minimized since similar slope conditions applied to all the sampling points. This observation is important for future works focused in the effect of topographic variation in soil moisture behaviors, since by selecting small landscape fragments heterogeneity among locations can be maximized.

Cosh et al. (2004) showed that uneven distribution of precipitation plays an important role in the soil moisture behavior of the point samples. Assuming similar soil conditions in large fields and unevenly distributed precipitation events over space, when compared with the mean of the field, dry points will receive less precipitation while wet points will be the ones with highest amounts of rainfall. When the study is conducted over short periods of time the distribution of rain-fall is especially critical, since the results will show points of temporal instability that over or under estimate the field mean. These observations support our methodological approach of using small plots as landscape objects for soil moisture variation.

In the case of site 66, portions of the plot are partially bare land, with an uneven vegetation cover mix of short grasses and weeds and eventually bushes that were mowed during some reading dates. In the field at site 16, some of the areas were affected by the transit of agriculture equipment, not only affecting the growth of the tall grass cover but also the compaction of the soil and the infiltration of water into the ground. These details in LULC may explain the range in the time stability showed by some of the point readings of these plots.

Alternatively, the stability in plots 50 and 40 can be explained by their relatively homogeneous land cover. Plot 50 forms part of a large pasture and the entire plot is covered by the same type of grass, while plot 40 is part of a mechanized agriculture field and changes in vegetation cover through the growing season. This homogeneous characteristic of vegetation cover, in addition to the homogeneity in precipitation, slope and soil physical properties, may contribute to the high stability of the soil moisture recorded at these two sites.

Twenty four hours soil moisture variations

The Pearson's correlation coefficient was computed to evaluate if all the infield locations experience similar soil moisture variations within a short time lag, in this case one day of difference. The results for the Pearson's correlation coefficient (Table 4) show clear differences in the wetting

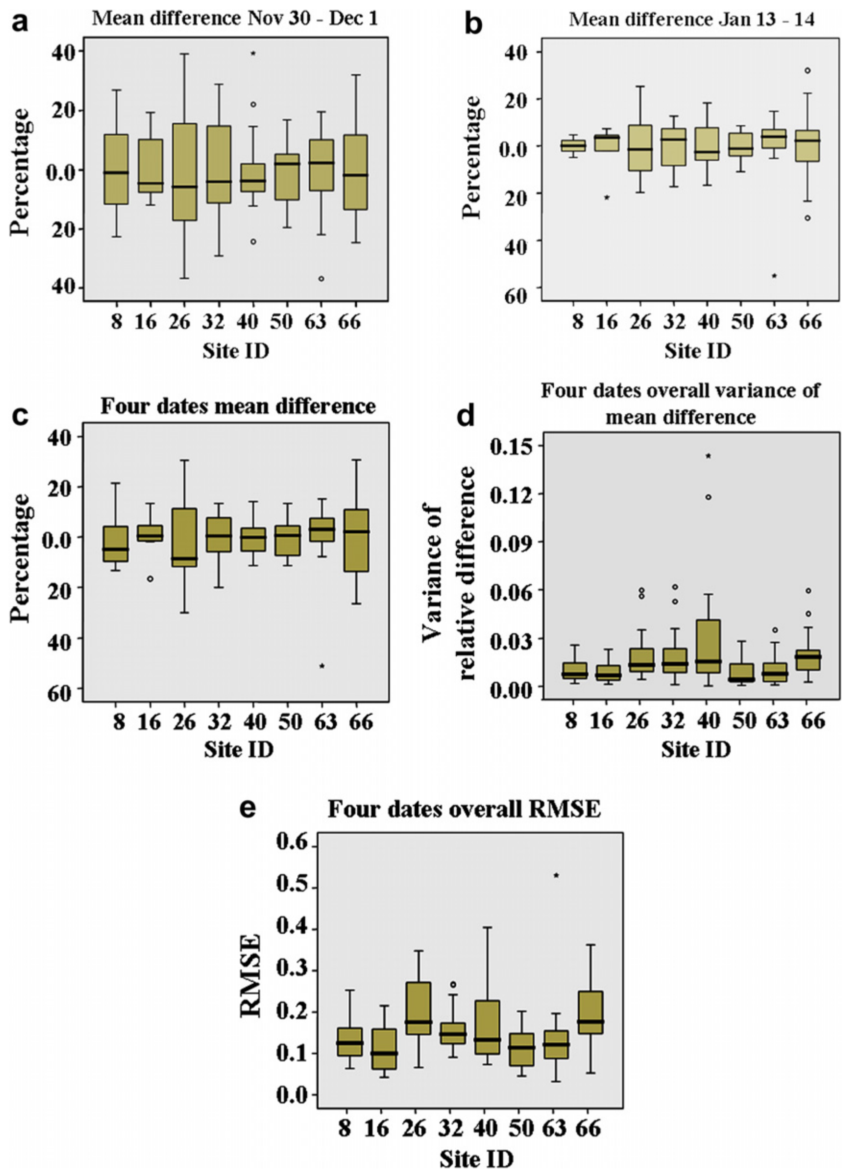

Figure 5 Mean relative difference in SM between pairs of simultaneous data (a and b) and overall difference from four field data collections together (c). Four dates of overall variance of mean difference (d) and root mean square error (e).

Table 4 Pearson's correlations of soil moisture paired samples

Site	November 30 and December 01, 2005			January 13 and January 14, 2006		
	N	Correlation	Significance	*N*	Correlation	Significance
8				12	0.449	0.143
16	14	0.434	0.121	9	0.699	**0.036**
26	20	0.710	**0.000**	20	0.598	**0.005**
32	20	0.671	**0.001**	20	0.618	**0.004**
40	15	0.549	**0.034**	16	0.307	0.248
50	18	0.324	0.189	18	0.252	0.314
63	20	0.707	**0.000**	15	0.697	**0.004**
66	19	0.564	0.012	17	−0.103	0.695

and drying characteristics among the sites, since the coefficients were significant in both sets of field data collections only for the samples collected from sites 26, 32 and 63 at the probability level greater than 0.05. Site 63 showed a stable correlation around 70% for both sets of readings, while sites 26 and 32 decreased their correlation levels from

71% and 67% for the first set to 60 and 62% for the second set, respectively. On the other hand, site 50 was the only site in which the Pearson's correlation coefficient was not significant at the probability level of 0.05 of higher for both sets of readings.

In general, the significance level for the computed correlations was higher for the set of data collected in November–December than for the set collected in January. In this regard, the rain-fall in the late afternoon of January 13 may help to explain the differences in the trends of the two sets of data. While in the November–December set water from precipitation had at least two days to enter and distribute into the soil profile, on January 14 this process was just at its earliest stages, showing an apparent uneven distribution along the sites.

The Pearson's correlation coefficient is an indicator of the spatial stability of the soil moisture point data. Low coefficients with low significance levels indicate that the process is unstable in space and for the time lag in which data were collected. However, since the average standard deviation for the point data and the mean relative difference for those five locations are small, point data from them can be used to infer infield conditions within the ranges of standard deviation and mean relative difference.

Two samples *t*-test

A two sample paired test was computed to evaluate the variation in average soil moisture values from one day to the next (Table 5). This analysis serves as an indicator of the difference between plots and the time required to produce infield soil moisture variation. The results for the November–December set of records showed no significant statistical difference at the 0.05 probability level for any of the plots. The maximum mean difference between two records for a field was less than 1.2%. For the January records, all plots showed statistical difference at the 0.01 probability level, with a maximum mean difference between two records of 6.8%.

The difference between both sets of field data can be explained by the precipitation prior to and during the data collections. For the November–December collections, the plots were in the process of drying out since rain occurred 24 h previous to the data collection. This rain was the last in a series of three consecutive raining days contributing more than 2.5 cm of water to the sites, with exception of sites 40 and 50 with less than 2.5 cm (Fig. 3b). On the January field data collection, the plots were in the process of wetting since no precipitation occurred in a period of 10 days previous to the field data collection until the evening of January 13. On that evening, 0.5–2 cm of rain was recorded for all the sites producing different soil moisture conditions on January 14, less than 18 h after the January 13 field collection.

The statistically significant difference found by the paired *t*-test comparing the January data collections indicate that after a precipitation event the process of water infiltration into the soil profile and the time required to produce infield soil moisture variation may takes less than 24 h for all the locations investigated. The lack of statistical difference for the November–December field data may indicate a fast process of drying out at the upper layer of the soil (0–10 cm) and a very low water holding capacity of the soil at all the eight locations. About 24 h appears to be sufficient for a water infiltration to occur to the deepest layers of the soil.

The results suggest that surface soil moisture will not necessarily reflect profile conditions considering the rapid process of water infiltration within the soil profile. Therefore, remote sensing retrieving algorithms based only in the direct or indirect quantification of surface conditions such temperature, or moisture may produce errors when used in this landscape. These errors can be minimized by incorporating into the remote sensing analysis data on precipitation events prior to data collection and infiltration analysis for the soil types predominant in the study area.

Table 5 Two sample *t*-test of soil moisture paired samples

	Mean	Standard deviation	Standard error mean	*t*	df	Significance (2 tailed)
November 30–December 1, 2005						
8						
16	1.10	2.24	0.60	1.845	13	0.088
26	−1.27	2.89	0.64	−1.968	19	0.064
32	−0.94	2.22	0.49	−1.889	19	0.074
40	−0.56	2.36	0.60	−0.930	14	0.368
50	−0.66	2.95	0.69	−0.956	17	0.352
63	−0.13	2.38	0.53	−0.253	19	0.803
66	0.48	3.21	0.73	0.664	18	0.515
January 13 and 14, 2006						
8	−6.71	3.12	0.90	−7.439	11	**0.000**
16	−1.93	1.33	0.44	−4.335	8	**0.002**
26	−6.81	3.32	0.74	−9.160	19	**0.000**
32	−3.12	1.93	0.43	−7.233	19	**0.000**
40	−1.85	2.30	0.57	−3.216	15	**0.006**
50	−1.57	2.46	0.58	−2.710	17	**0.015**
63	−4.68	3.07	0.79	−5.909	14	**0.000**
66	−6.76	2.21	0.53	−12.575	16	**0.000**

Directional effects within plots

In this analysis, soil moisture point measurements were grouped according to the direction in which the reading was taken. A minimum of two and a maximum of five directions were considered for each site. The directions were coded using the number of the site followed by the position of each point sample in the sequence of readings. Fig. 6 shows for each site the behavior of the mean volumetric soil moisture distribution for each direction at each sampling date. The descriptive statistics for this analysis shows that for sites 8, 16, 26, 32, 63 and 66 at the directions 82, 161, 261, 324, 632 and 664 the soil moisture mean was higher

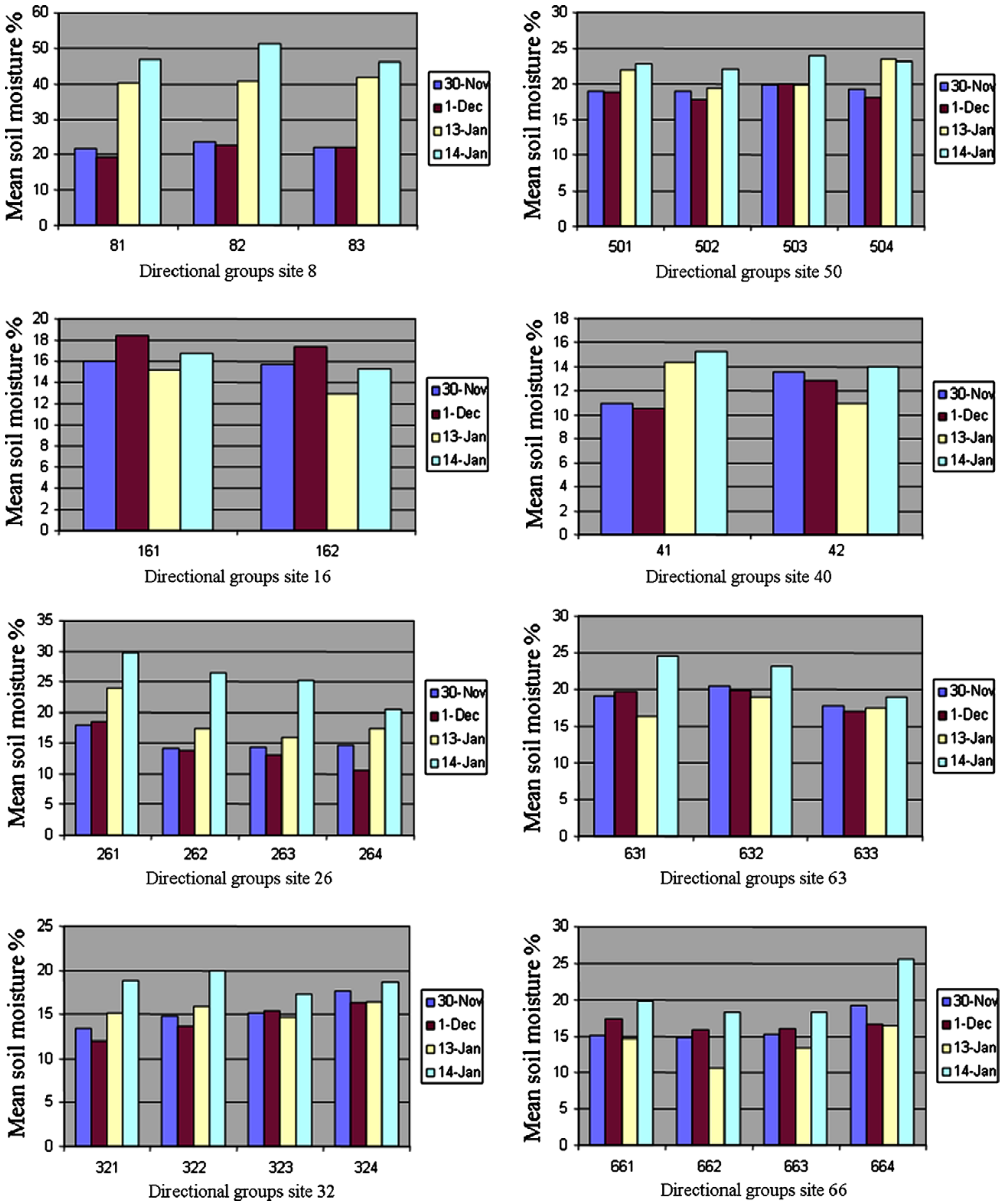

Figure 6 Mean volumetric soil moisture for directional groups analyzed at each site for four dates of readings.

than the other directional means on the same plot in at least three of four reading dates. Site 50 was the only plot in which the directions have a random behavior with no characteristic trend.

Using a general linear model with factorial components, the statistical significance of the directional trends observed in the soil moisture within the plots was analyzed. The factorial ANOVA shows that for sites 8, 16 and 63, there is no significant difference at the probability level of 0.05 for the mean soil moisture values among directions for any of the four reading dates. Site 26 was the only site in which statistical difference was found in at least three of the four reading dates. The post hoc Tamhane test showed direction 261 statistically different from the other three directions considered for this site. These point readings are located close to an access road on which there is frequent transit of agriculture equipment that may have altered the soil physical characteristics in terms of structure and compactness.

At site 66, soil moisture in directions 662 and 664 were statistically different from each other in two of the four reading dates. Direction 664 corresponds to a portion of the plot covered by a mixed vegetation that is 60 cm tall and periodically mowed to the ground, while direction 662 is in the open portion of the plot with almost no vegetation cover present during the sampling dates. This analysis supports the previous observations of the differential effect that LULC may have in the soil moisture behavior even in small areas.

Statistical analysis for agriculture landuse transects

Descriptive statistics

Table 6 shows the descriptive statistics for soil moisture on four different dates collected on 25–30 m long transects associated with five different agriculture field landuses adjacent to five plot areas. The results shows the orchard and grass transects associated with Hydra probe sites 32 and 50, respectively, have the wettest conditions, while transects through the peanuts and cotton fields (Hydraprobe site 40), were the driest. The tilled agriculture fields showed the lowest spatial variability with average values around 1%, while the transect through the grass agriculture field presented the highest standard deviations with values between 1.8% and 2.6%. The transect studied at the bareland field exhibited an intermediate behavior, tending to group with the wettest landuses rather than with the driest LULC.

Soil moisture variation between landuses

The ANOVA between the soil moisture values observed for the five 25–30 m LULC transects showed significant statistical differences for all four dates (0.01 probability level). This is an indicator of high variability existing between the soil moisture response among the five transects. On the other hand, the lowest scores of the mean square within groups indicate very low variation between the sampling points within a landuse. The highest differences between

Table 6 Descriptive statistics for volumetric (%) soil moisture in transects associated with five landuses

	N	Mean	Standard deviation	Standard error	95% confidence interval for mean		Minimum	Maximum
					Lower bound	Upper bound		
11/30/2005								
Orchard	8	16.8	2.09	0.7401	15.075	18.575	14.5	21.3
Cotton	7	13.8	1.65	0.6248	12.300	15.357	11.3	15.8
Peanut	8	13.6	1.00	0.3546	12.812	14.488	12.0	14.6
Grass	10	19.1	2.18	0.6905	17.558	20.682	16.1	22.7
Bare land	8	16.1	1.68	0.5973	14.738	17.562	14.3	19.3
12/01/2005								
Orchard	8	16.2	1.65	0.5858	14.852	17.623	14.0	18.4
Cotton	7	12.7	1.11	0.4217	11.754	13.818	11.8	15.0
Peanut	8	11.4	1.32	0.4671	10.345	12.555	9.0	12.8
Grass	10	17.9	2.21	0.7013	16.344	19.516	13.6	21.3
Bare land	8	16.4	2.17	0.7704	14.616	18.259	12.4	18.9
01/13/2006								
Orchard	8	17.7	2.49	0.8805	15.643	19.807	15.2	22.0
Cotton	8	14.2	1.37	0.4864	13.137	15.438	11.7	15.9
Peanut	8	13.2	0.83	0.2958	12.538	13.937	11.9	14.5
Grass	8	21.5	2.58	0.9149	19.374	23.701	17.7	24.7
Bare land	8	10.1	2.06	0.7317	8.370	11.830	8.1	14.4
01/14/2006								
Orchard	8	19.1	0.91	0.3224	18.338	19.862	18.0	20.9
Cotton	8	14.5	0.87	0.3087	13.845	15.305	13.4	15.6
Peanut	8	14.5	1.16	0.4131	13.586	15.539	13.1	16.6
Grass	8	23.0	1.79	0.6336	21.564	24.561	19.4	24.8
Bare land	8	17.2	1.48	0.5258	16.007	18.493	14.7	18.9

Table 7 Tukey groups of similar soil moisture conditions

Transects	Grass	Peanut	Cotton	Orchard	Bare soil	Total
Grass		0	0	2	1	3
Peanut	0		4	0	0	4
Cotton	0	4		0	0	4
Orchard	2	0	0		3	5
Bare soil	1	0	0	3		4
Total	3	4	4	5	4	

landuses were found in the field data collection conducted in January with scores almost twice as high as from the November–December data collection.

A Tukey–Tamhane analysis of means was used to explore, in more detail, the variability between groups showed by the ANOVA (Table 7). The LULC transect to transect comparison showed transects from agriculture fields, peanuts and cotton, as the most similar with no statistical difference among them for any of the four reading dates. Also, these transects had the greatest differences with orchard, grass and bare land showing statistical differences on all the sampling dates. Orchard and bare land showed similarity for three of the reading dates, while orchard and grass were similar for only two of the reading dates. Soil moisture data from the grass and orchard fields were consistently higher than in the agriculture and bare-land fields during the November–December reading. For the January reading, data collected from the grass and orchard fields still presented the highest soil moisture contents, although with more than 3% difference of average volumetric soil moisture between them. On the January 14th sampling, the difference in soil moisture was of 1.8% between orchard and bare land.

A one sample t-test was performed to compare the relationship between the average soil moisture for the agriculture field transect with the mean soil moisture obtained from the closest 30 by 30 m sampled plot. In this analysis, the test value for t-test corresponds with the average soil moisture of the field for a given date.

This analysis consistently showed no significant difference between transects of grass and its corresponding adjacent 30 by 30 m plot. Peanut transects were not different in three reading dates, while bare land was different on only two reading dates. On the other hand, cotton and orchard showed significance differences with their adjacent plots for three of the four soil moisture readings. This analysis indicates that regardless of the spatial proximity between two homogeneous fields, LULC is a factor affecting the soil moisture behavior. This is an important observation suggesting that the point readings from the stations of the in situ network cannot be interpolated to nearby locations exclusively under criteria of proximity. LULC is an element that contributes to the landscape complexity and as demonstrated in this research, to the spatial and temporal variation of soil moisture at the local scale.

Discussion and conclusions

The combination of environmental variables such as soil type, vegetation cover, topography and climatic condition create spatially distributed patterns of soil moisture varying over different scales of space and time (Qiu et al., 2003; Anderson et al., 2004). As a consequence, soil moisture is not a random phenomenon, but a spatially organized one in which the spatial variability of its response varies according to the size of the sampled areas and the characteristics of the environmental variables that produces it (Western and Bloschl, 1999).

Accurate long term study of the environmental cycles and the calibration of remote sensing data using the in situ network of soil moisture stations operated by the USDA-ARS-SEWRL near Tifton, Georgia rely on understanding the relationships between the point field data and the surrounding landscape. Defining the geographic extent of a moisture field that is represented by a point sample as measured by a typical monitoring system has been a critical topic of investigation that is needed to advance the process of retrieving and validating soil moisture estimates from remote sensors (McCabe and Wood, 2006; Moran et al., 2004).

Under field conditions with homogeneous soil texture, vegetation cover and hill slope, studies demonstrate that single point measurements can accurately represent the average soil moisture of an entire agriculture field and, therefore, be useful under certain spatial ranges to calibrate soil moisture estimates from remote sensing instruments (Western and Bloschl, 1999; Jacobs et al., 2004). However, in spatially heterogeneous landscapes, high spatial and temporal variation in soil moisture behavior is created by the combination of precipitation, landuse-land cover (LULC), soil type and topography that change over distances of less than a few hundreds of meters (Western et al., 2004; Pauwels et al., 2001).

In this research, the eight selected locations received similar rainfall amounts during the 12 days prior to the eight data collections, therefore, soil moisture variations among plots were not the consequence of rainfall variations and the soil moisture behavior was expressed according to the site specific dynamics of water into the soil profile. Likewise, as a consequence of the small area covered by each field, by selecting 30 by 30 m plots, topographic variations in slope steepness and even to a certain degree soil physical properties were minimized. Therefore, landscape complexity was minimized at the local scale and homogeneous spatial and temporal soil moisture conditions were identified at all of the eight study locations confirming the research hypotheses.

ANOVA and post hoc analysis show high differences in soil moisture conditions among the plots, but also similarities among pairs of locations despite their spatial separation. Similarities among pairs of locations can be attributed to similar LULC, soil type or both. On the other hand, using temporal stability analysis, this study demonstrated that within the 30 by 30 m plot a single point reading can be used to infer average field conditions with less than 3% v/v soil moisture variation between infield readings. The two pair t-test showed that all eight locations experienced soil moisture variations in the upper soil layer (0–10 cm) in less than 24 h, indicating a fast process of water movement into the soil profile. This observation should be further investigated since soil moisture conditions in the upper soil layer do not necessarily correspond with soil water contents at the deepest layers, and therefore, to establish hydrological conditions or water status in this landscape using remote sensing data alone may not be sufficient. When monitoring surface soil moisture conditions in short time intervals (<24 h) specially, after rainfall events, the lack of significance in the Pearson's correlation coefficient for most of the eight plots suggests the need to include readings from more than a single point location to decrease errors in estimating soil moisture conditions. Also, portions of the areas affected by external factors (i.e., human activities) should be avoided since they may present different soil moisture conditions.

The analysis of soil moisture conditions within five LULC transects confirmed the hypothesis that homogeneity in soil moisture can be found in small areas regardless of their LULC. In addition, similarities and differences in soil moisture behavior can be found among different LULC that can not be explained completely by the type of vegetation cover. This result serves a first step in the process of identifying the origins of individual soil moisture dynamics, that acting at the local scale, can be associated with particular portions of a complex and diverse landscape towards an appropriate long term evaluation of regional soil moisture behaviors.

In this context, continuing with the studies of small plots around each one of the Hydra-probe in situ stations will help to assess the characteristics of the field that each reading station is representing in the landscape. In this approach, each reading station can be used as an indicator of a particular combination of precipitation, LULC, soil and topography that operating at the local scale has several replicates through the landscape. Combining groups of similar soil moisture behavior is expected to produces an accurate representation of the soil moisture dynamics at the landscape scale.

The methodology of using small plots as landscape units of soil moisture conditions is in agreement with landscape ecology theory in which complex systems are described by decomposing them into their fundamental parts (fragments) and interpreting their interactions (Hay et al., 2002). Homogeneous fields are, in our case, areas of spatial organization within the landscape in which a soil moisture behavior can be identified. Since landscape fragments are the units of spatial resolution in which biophysical factors interact, the pixel oriented approach used in LULC and environmental analysis with remote sensing data has the disadvantage that pixels do not correspond with ecological units of spatial organization. Therefore, for further research of soil moisture using remote sensing data, we consider that a landscape ecology approach that considers the sizes and composition of landscape units (LULC fragments, patches or fields) is required in the remote sensing image processing of this landscape.

Under landscape ecology approach and using the technical capabilities of geographic information systems, the assessment of plots of similar soil moisture behavior will reduce the amount of uncertainty associated with regional representations of soil moisture based merely on geostatistics formulations (Western et al., 1990). In this way, we consider that the study of LULC fragments will positively impact current and future remote sensing soil moisture retrieve algorithms in two ways. First, when soil moisture is indirectly estimated from fine spatial resolution remote sensing data using surrogated variables such as surface radiant temperature ((Li et al., 2004; Park et al., 2004) or the combination of surface temperature and vegetation indexes (Carlson et al., 1995; Merlin et al., 2006). In this case, the accurate assessment of the environmental variable vegetation cover acting at the scale of the LULC fragments will provide more accurate and realistic data to feed soil moisture extraction algorithms. Second, when soil moisture readings are obtained with coarse resolution remote sensors, since, it will increase the accuracy of disaggregating data where image pixel combines spectral information from different land covers (Kustas and Norman, 2000; Merlin et al., 2006). In this case, the mismatching between ground point field data and satellite pixels will be avoided allowing the direct linking of ground field data with the unit areas of a remote sensor, providing a better assessment of the soil moisture data retrieved by different satellite and aircraft sensors.

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